

# Transmittance as a Function of Water and Oxygen Levels in the VUV Regime

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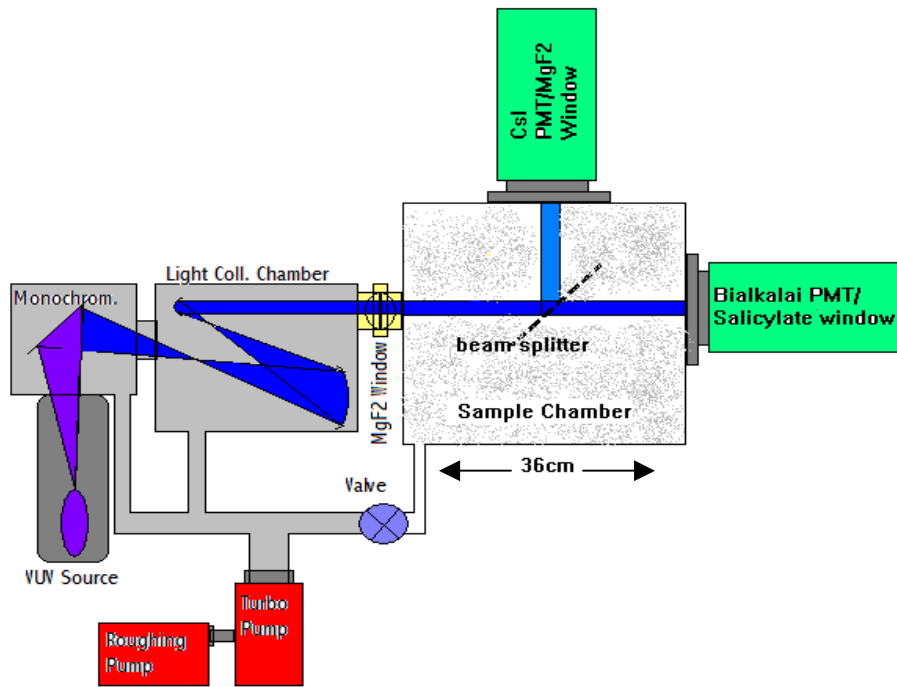
## Introduction

In the production of a gas Cherenkov detector, in addition to choosing a gas radiator which is transparent to the emitted Cherenkov light, it is also vital to know what levels of contaminant particles can be tolerated in the construction of the final detector. Because a guiding principle behind the construction of most inner detectors consists of minimizing the radiation length, the detector vessel often must be produced mostly of plastic materials. Besides the initial problem of out-gassing, a more critical concern is the ability to withhold air from the inner working gas of the detector. Although miniscule amounts of nitrogen usually pose no absorbance issues within the detector, the small portions of water vapor and oxygen that are able to cross the less than perfect gas seals can potentially be disastrous in terms of absorption of the emitted Cherenkov light. As a result, given the materials one has to work with, a lot of attention must be brought to the design and construction of this gas seal. The following study, therefore is intended to act as a reference to make one aware of what levels of water and oxygen can be tolerated within the detector, before significant amounts of signal are lost.

## Method

In this study, the transmission of light through gas contaminated with water vapor and oxygen is quantified by the *transmittance*, which is the ratio of the flux coming from a given light source, to the flux detected after the light has traversed a given length through some gas absorber. Since the Cherenkov spectrum has an ascending output into the deep UV, a VUV spectrometer is utilized with a dynamic range of 110 – 400nm, to scan the gas over the wavelengths between 110 and 200nm. The basic design of the set-up used here is outlined in Fig. 1 below, and consists of a VUV spectrometer coupled to a 36cm long sample chamber equipped with two photomultiplier tubes to detect the flux at

each dispersed wavelength. This set-up enables back to back scans taken while the sample chamber is filled with gas to one atmosphere, and pumped out to high vacuum ( $\sim 5.0 \times 10^{-6}$  Torr). At this pressure, the vacuum scan very well approximates a direct measurement of the D<sub>2</sub> lamp flux to well below one tenth percent when considering the loss of some photons to the few gas particles still present in vacuum. Due to the dependence of the photocathode quantum efficiency on the wavelength, the PMT current during each scan is *relatively* proportional to the detected flux. However, once the ratio of currents from both the vacuum and sample scans are taken, the quantum efficiency drops out, leaving an absolute measure of the transmittance.



**Figure 1: Spectrometer/Sample Chamber:** As VUV light is emitted by the pressure broadened D<sub>2</sub> lamp source, it is focused onto a diffraction grating which disperses the light into component wavelengths, that are then fed through a narrow bandpass slit into an adjacent chamber containing VUV collimating optics. Once the collimated light passes through a (VUV transparent) MgF<sub>2</sub> window which acts a gas barrier, the beam then traverses 36cm of gas before illuminating the windows of two different PMT's. Although the beam intercepts and is split by a VUV beam splitter, the path length to the two PMT windows is the same. The CsI PMT is operated in photodiode mode and acts a monitor to insure stable operation of the data taking PMT. The CsI PMT is equipped with a MgF<sub>2</sub> window and a CsI photocathode with high quantum efficiency in the VUV. The data collecting PMT is a bialkali PMT which uses a salicylate coated window to convert VUV light into visible light, that is measurable by the bialkali photocathode. The photocathode active area is many times larger than the beam cross section for both PMT's. Because the index of the sample gas (Ar)  $\sim 1.00$ , the position of the beam on the salicylate window is not shifted due to dispersive effects and is the same during both gas and vacuum scans

Because the two scans are taken at two different points in time, the measurement becomes susceptible to instrumental drift in the PMT and/or the D<sub>2</sub> lamp. In order to factor out the effects of instability in the PMT, two PMT's are used in conjunction with a

VUV beam splitter. The CsI PMT acts as a monitor and is operated in photodiode mode, where all of its dynodes are shorted together, and the gain fluctuations are factored out. Although it would have been preferable for this PMT to continually monitor the dispersed D<sub>2</sub> lamp output in vacuum, it was not possible to construct the required apparatus. As a result, many consecutive scans have been taken in vacuum over the course of a few days, with the conclusion that the lamp's output is stable to within one percent over the course of the time it takes to make two scans back to back.

After baseline measurements of the transmittance were performed using Ar as the balance gas, where the concentration of water and oxygen were at their minimum attainable values ( $[H_2O] \sim 10\text{ppm}$ , and  $[O_2] < 1\text{ppm}$ ), minute amounts of water and oxygen were then pumped into the sample chamber in a series of two independent measurements. First, the oxygen levels were intentionally elevated (in steps of tens of ppm's), while the water levels stayed more or less constant, and a family of transmittance curves were produced at differing oxygen levels. The same was done for varying water levels and constant oxygen levels. The illustration below in Fig. 2 depicts the method by which water vapor and oxygen were independently injected into the sample chamber.

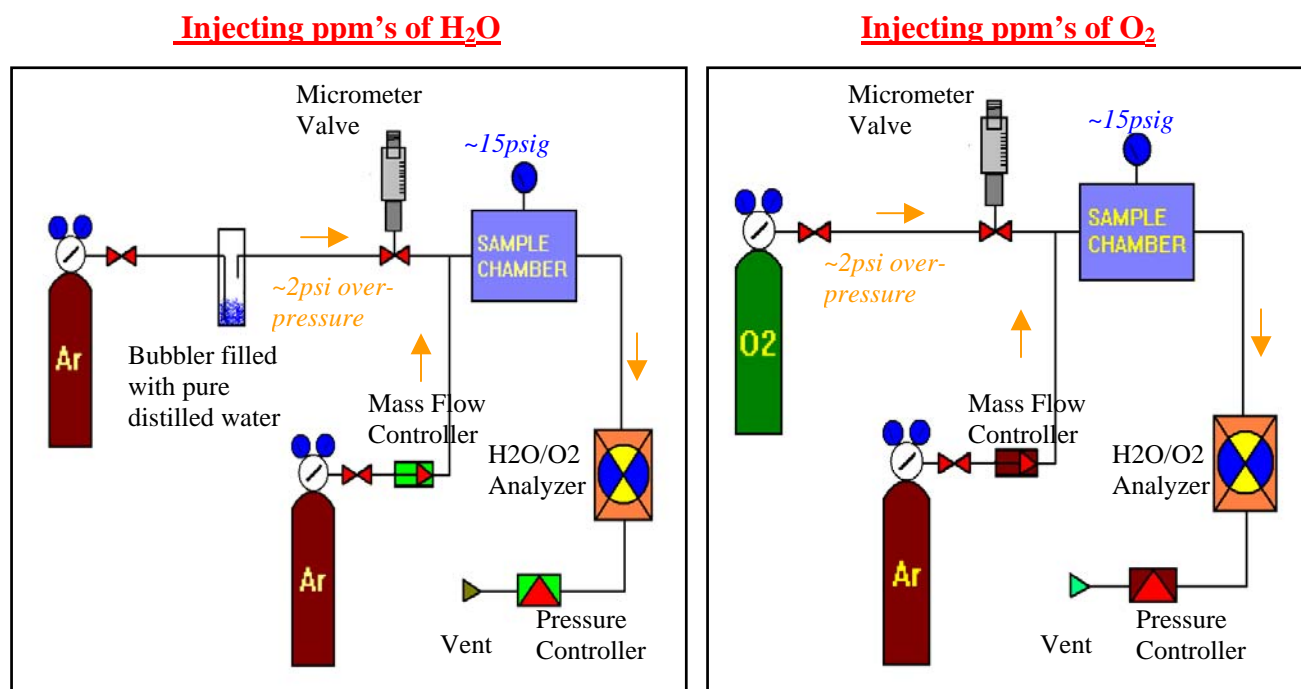


Figure 2: The schematics above depict the two gas systems used to inject water and oxygen respectively into the sample chamber. A) In the case of injecting water, as pure (4.8 grade) Ar continually purges through the system at  $\sim .500\text{SLPM}$ , a secondary (4.8 grade) Ar bottle bubbles through a bubbler filled with distilled water. The apparatus is kept at room temperature, resulting in relatively high water vapor pressure in the output line of the bubbler. The resulting water content in this line approaches  $10,000\text{ppm } H_2O$ . The amount of water injected is then regulated by over-pressuring this line to  $\sim 1\text{-}2\text{ psi}$ , while controlling the flow to high precision using a micrometer needle valve. To get progressively higher levels of water into the sample chamber, the micrometer valve is steadily opened further. B) Injecting oxygen follows the same basic method, but instead of flowing Ar through a bubbler, the secondary gas input line is over-pressured with pure (4.0 grade) oxygen.

After setting the following parameters: the O<sub>2</sub>/H<sub>2</sub>O input line pressure, the micrometer valve opening, and the Ar flow rate, the gas was allowed to flow on the order of 18 hrs. in order to allow the water and oxygen analyzers to stabilize and yield accurate readings. A transmittance measurement was then only made once the analyzers were observed to yield stable readings for at least an hour. The water and oxygen levels were then read off the respective analyzers before and after the gas scan, where the average is the quoted level. The quoted levels were observed to be stable to below +/- 1ppm.

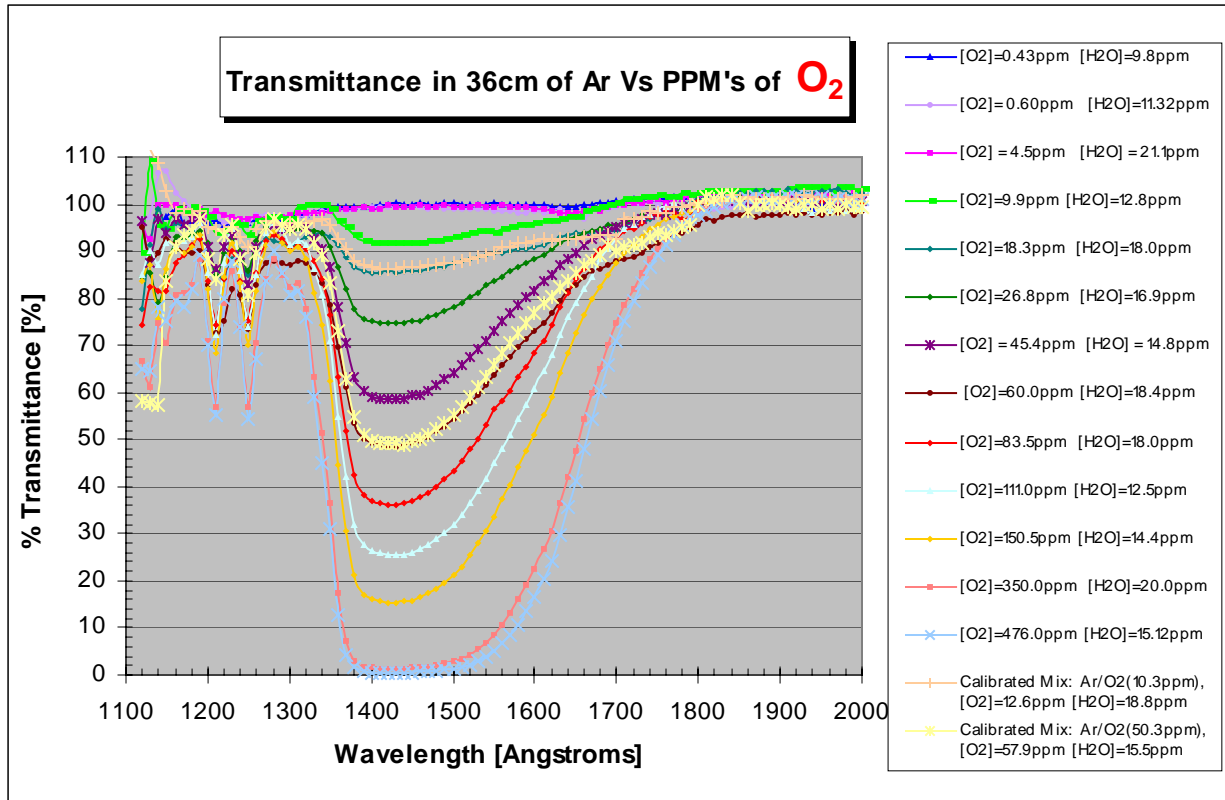
## Theory

The probability that a photon will interact with a particle is proportional to the interaction cross section,  $\sigma$  for a given interaction. In the VUV regime, where the photon energy is on the order of 10eV, the interactions between photons and matter with the dominant cross sections are the photoelectric effect and Rayleigh (coherent) scattering. In addition to the probability of an interaction between a material particle and a photon, the actual number of interactions is also mediated by the number of particles or interaction centers present. Both of these concepts are encompassed by the following expression:  $I(x) = I_o e^{-\mu x}$ , where  $I(x)$  is the flux after the beam has traversed a distance  $x$  through the absorber,  $I_o$  is the initial flux, and  $\mu$  is the attenuation coefficient. In terms of  $\sigma$ , the same expression may be written:  $I(x=L) = I_o e^{-\sigma N L}$ , assuming the gas and its contaminants behave as an ideal gas with no interatomic interactions; where  $N$  is the particle density (particles per cm<sup>3</sup>), and  $L$  is the total length through which the VUV beam travels. Now, since the interaction cross section for Ar atoms is negligible compared to that for water and oxygen, this expression should only take into account the water and oxygen interaction centers. Since by design we insure that the water levels are low during the scans with elevated O<sub>2</sub> levels, and vice versa, we may further take into account the water and oxygen cross sections one at a time. In order to determine the number of such interaction centers per cubic centimeter, we multiply  $N$  for an ideal gas at room temperature and atmospheric pressure ( $2.59 \times 10^{19}$  cm<sup>-3</sup>) by the ppm's of the contaminant expressed in terms of a fraction,  $p$ . Thus the expression above becomes:  $I(x=L) = I_o e^{-\sigma p N L}$ , where the quantity  $p N L$  represents the total number of interacting centers the beam will encounter over the cross section of the beam through the gas. Multiplying this quantity by  $\sigma$ , then returns the total number of interactions the beam will endure during its trip through the gas. Thus, the preceding expressions and the following results depend only upon the number of interacting centers present within the gas and not necessarily on the balance gas itself, as long as the gas and its contaminants together may be treated ideally.

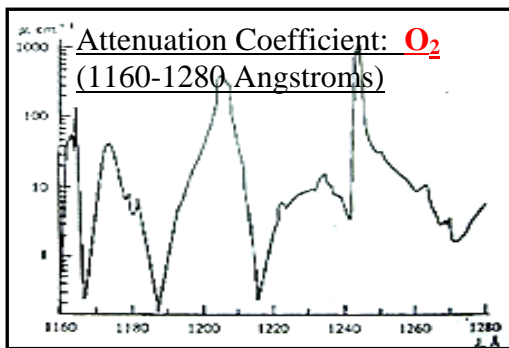
## Results

The following plots depict the measured transmittance spectra at differing water and oxygen levels. For comparison, the interaction cross sections for both water and

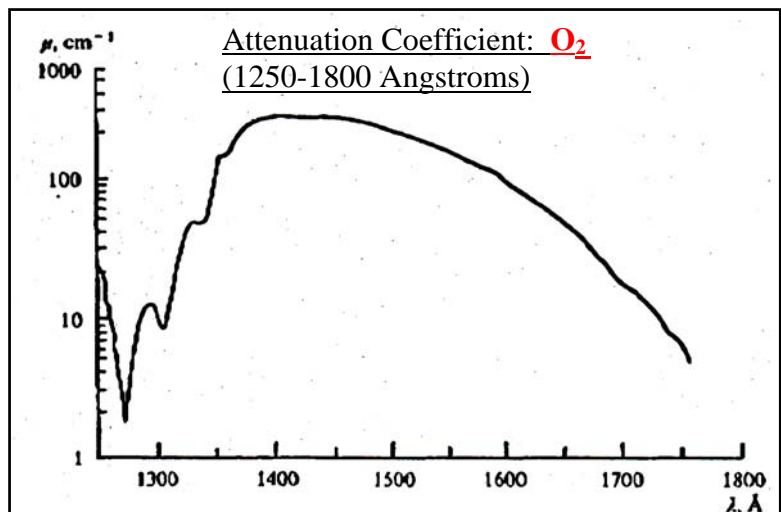
oxygen are included from the prevailing literature [1], and reflect the overall trend in the data. The integrated transmittance is also determined from the data and plotted Vs wavelength. Finally, in order to test the consistency of the data with respect to the values published in the literature [1], the transmittance at one specific wavelength is plotted beside a transmittance curve, generated from the expression above and the cross section taken from the literature. Furthermore, two transmittance spectra were generated using



**Figure 3: Transmittance spectra as a function of  $O_2$  levels. Included are two spectra taken with Ar gas with calibrated levels of  $O_2$  at 10.3ppm, and 50.3ppm, nominally. A single distinctive broad absorption band is evident at 145nm, and two narrower ones at 125, and 121nm.**

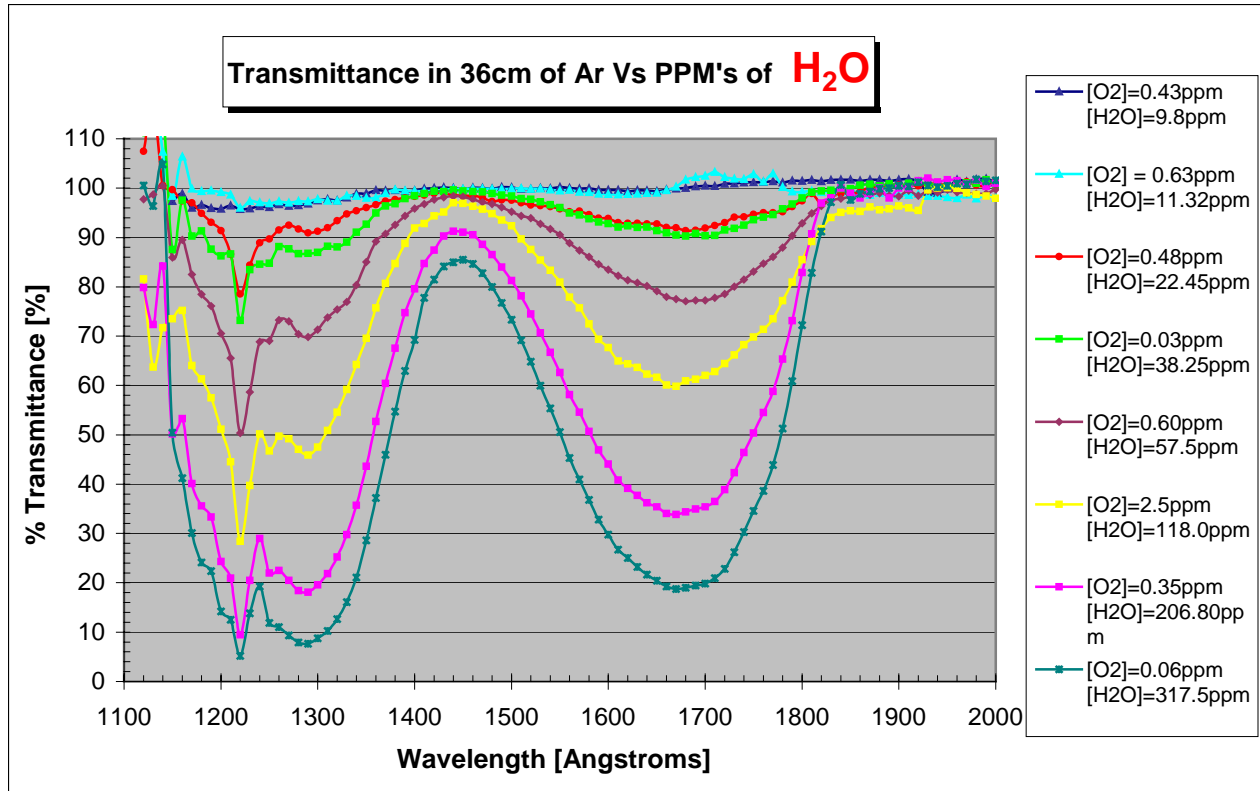


**Figure 4: Attenuation coefficient,  $\mu$  [cm<sup>-1</sup>] Vs wavelength [Angstroms] for  $O_2$ . Extracted from [1].**

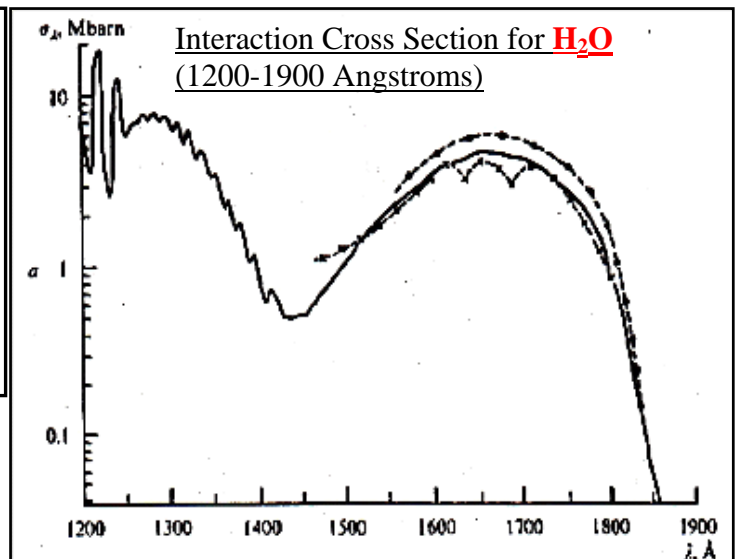
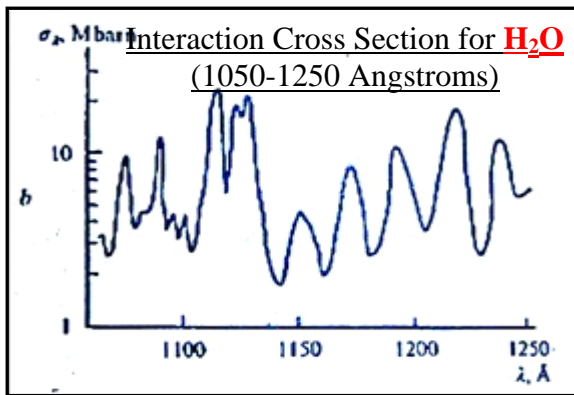


two company certified Ar/O<sub>2</sub> mixed gases, with ~10ppm's and ~50ppm's of O<sub>2</sub> respectively. As before, data is extracted from these two spectra as well and portrayed in the same accompanying plots just described.

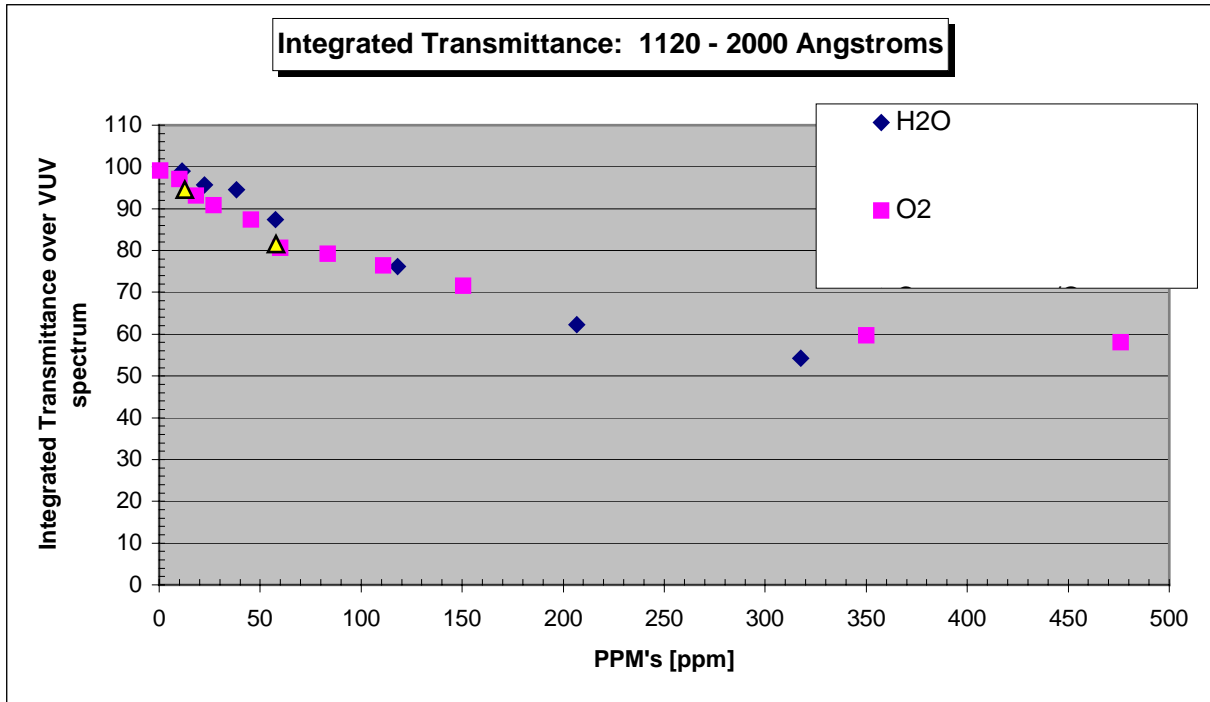
The propagated error determined from the transmittance calculation is  $\sim \pm 1\%$  ( $1170 < \lambda < 1725$  Angstroms), and  $\pm 2$  to  $5\%$  ( $\lambda < 1170, \lambda > 1725$  Angstroms).



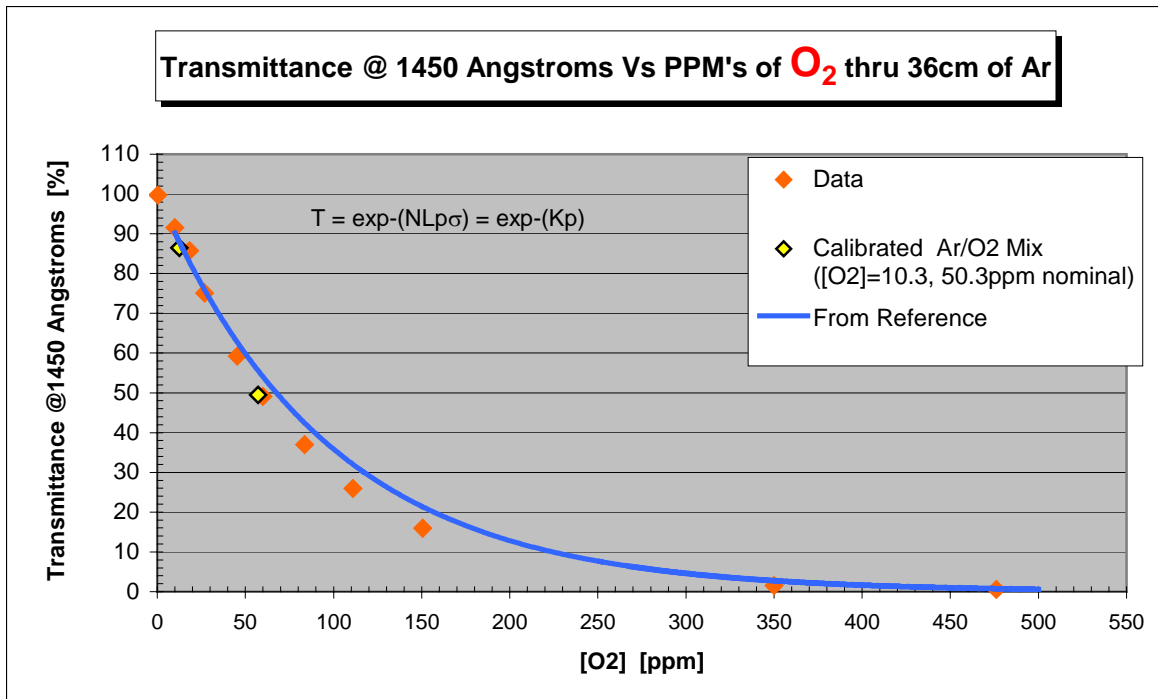
**Figure 5:** Transmittance spectra as a function of H<sub>2</sub>O levels. Two distinctive, broad absorption bands are evident at ~170nm and 125nm, and narrower bands below 125nm.



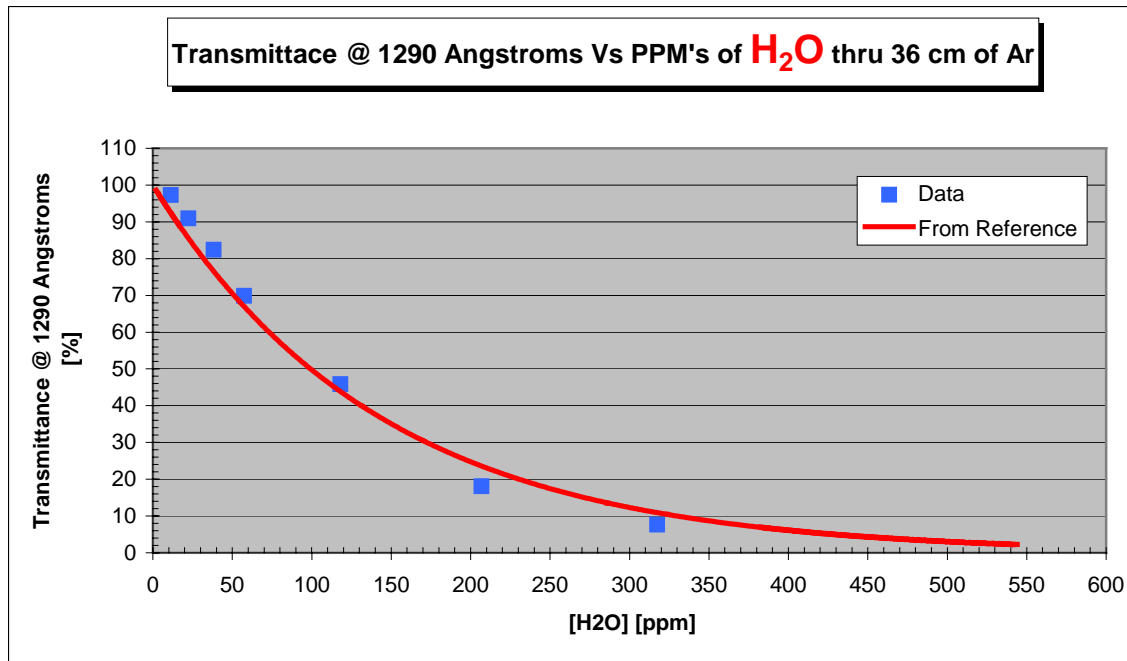
**Figure 6:** Interaction cross section,  $\sigma$  [Mbarn] Vs wavelength [Angstroms] for H<sub>2</sub>O. Extracted from [1].



**Figure 7: Integrated Transmittance calculated from transmittance spectra.**



**Figure 8: Transmittance data @1450 Angstroms Vs  $O_2$  levels, compared to the expected transmittance--calculated from the attenuation coefficient @1450 Angstroms, extracted from the plot in Fig. 4.**



**Figure 9: Transmittance data @1290 Angstroms Vs H<sub>2</sub>O levels, compared to the expected transmittance--calculated from the interaction cross section @1290s Angstrom, extracted from the plot in Fig. 6.**

## Conclusions

As mentioned, the results above have been verified by two independent sources, one being the interaction cross section for H<sub>2</sub>O, and the attenuation coefficient for O<sub>2</sub> extracted from [1], and the other being two transmittance measurements taken with two Ar bottles, each with (company certified) calibrated levels of O<sub>2</sub>, at roughly 10 and 50 ppm's. It is therefore clear from these results that, in order to preserve 95% of the Cherenkov signal, the detector should be operated at oxygen and water levels of no more than 10 and 15ppm's respectively. These number correspond to a 36cm absorption length of course, however these results may be extrapolated to longer and shorter absorption lengths by simply using the data above to calculate the interaction cross section for both water and oxygen.

## References

<sup>1</sup> A.N. Zaidel' and E.Ya. Shreider, *Vacuum Ultraviolet Spectroscopy*. Ann Arbor-Humphrey Publishers; Ann Arbor, London 1970.